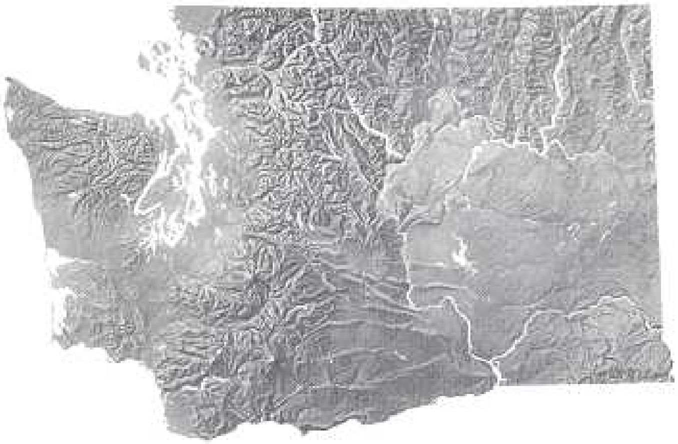

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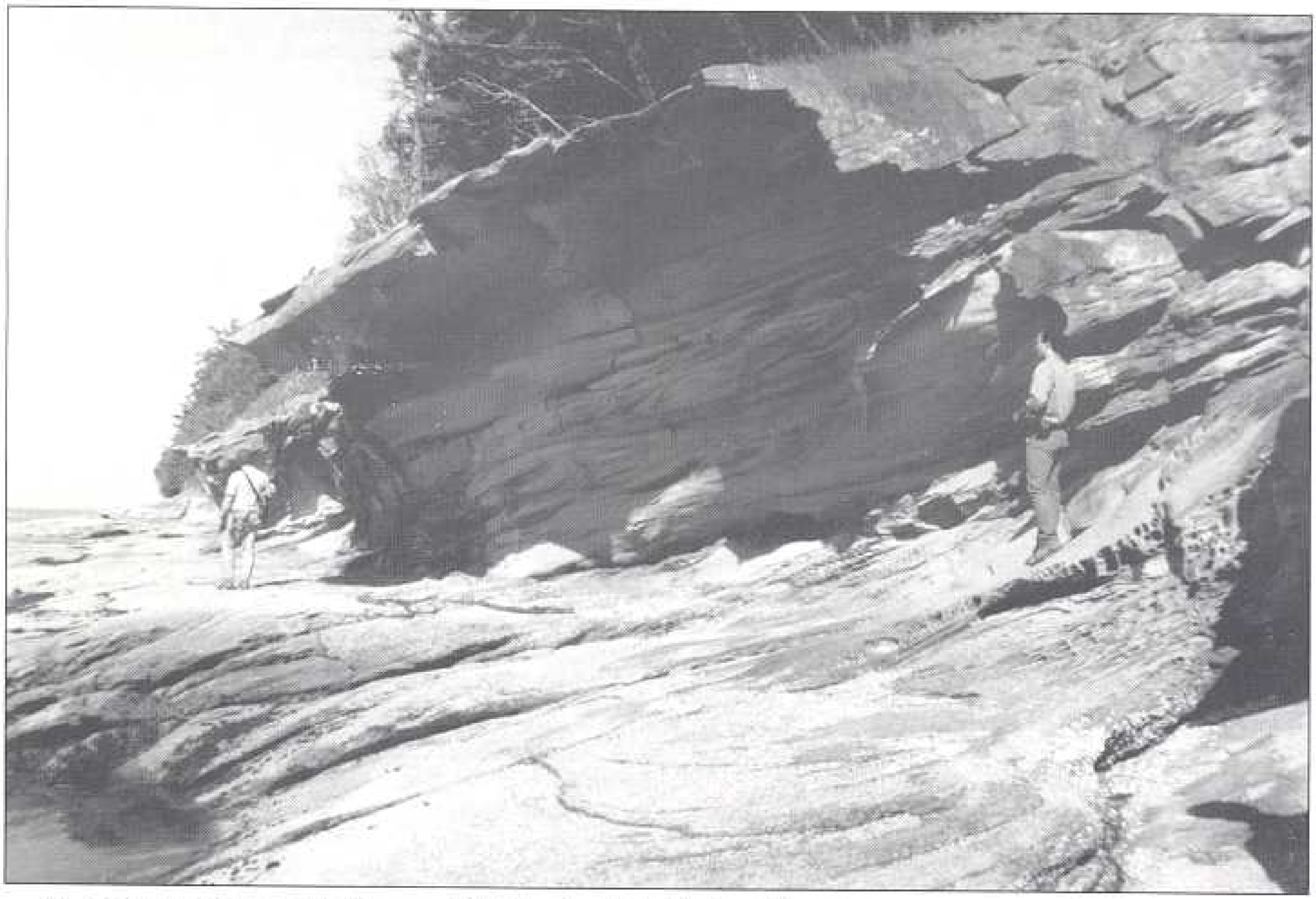

Cross-bedded sandstone of the Governors Point Member of the Chuckanut Formation at an outcrop west of Bellingham. S. Y. Johnson (USGS) interprets these as braided river deposits; their source was a rapidly eroding highland on and near Lummi Island. See related article, p.12. Photo by T. J. Walsh.

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Geology and Preliminary Hydrocarbon Evaluation of the Tertiary Juan de Fuca Basin, Olympic Peninsula, Northwest Washington

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The Juan de Fuca basin (JDFB) extends from near Striped Peak northwestward to Cape Flattery along the northern margin of the Olympic Mountains (Fig. 1). This Tertiary deep marginal basin continues north and northwest beneath the Strait of Juan de Fuca and the Pacific Ocean to the Canadian shelf and slope and is referred to as the Tofino basin (TB) by Shouldice (1971) and the Tofino–Fuca basin by Snavely and others (1980). The northern flank of the JDFB–TB is exposed in a narrow belt of shallow- and deep-marine Paleogene and early Neogene strata that crop out along the southern coast of Vancouver Island (Snavely and others, 1980; Cameron, 1971, 1979; Bream, 1987). The JDFB may have extended farther east at times (De Chant, 1989) and (or) may have been connected with other deep-marine basins that had different sediment source areas (Snavely and others, 1980).

The southern flank of the JDFB consists of more than 6,000 m of homoclinal north-dipping strata of middle Eocene to early Miocene age (Brown and others, 1960; Gower, 1960; Snavely, 1983; Snavely and others, 1986, 1989). Lithic arkosic to lithic turbidite sandstone, deep-marine mudstone, and subordinate polymict conglomerate and sedimentary breccias unconformably overlie lower Eocene oceanic

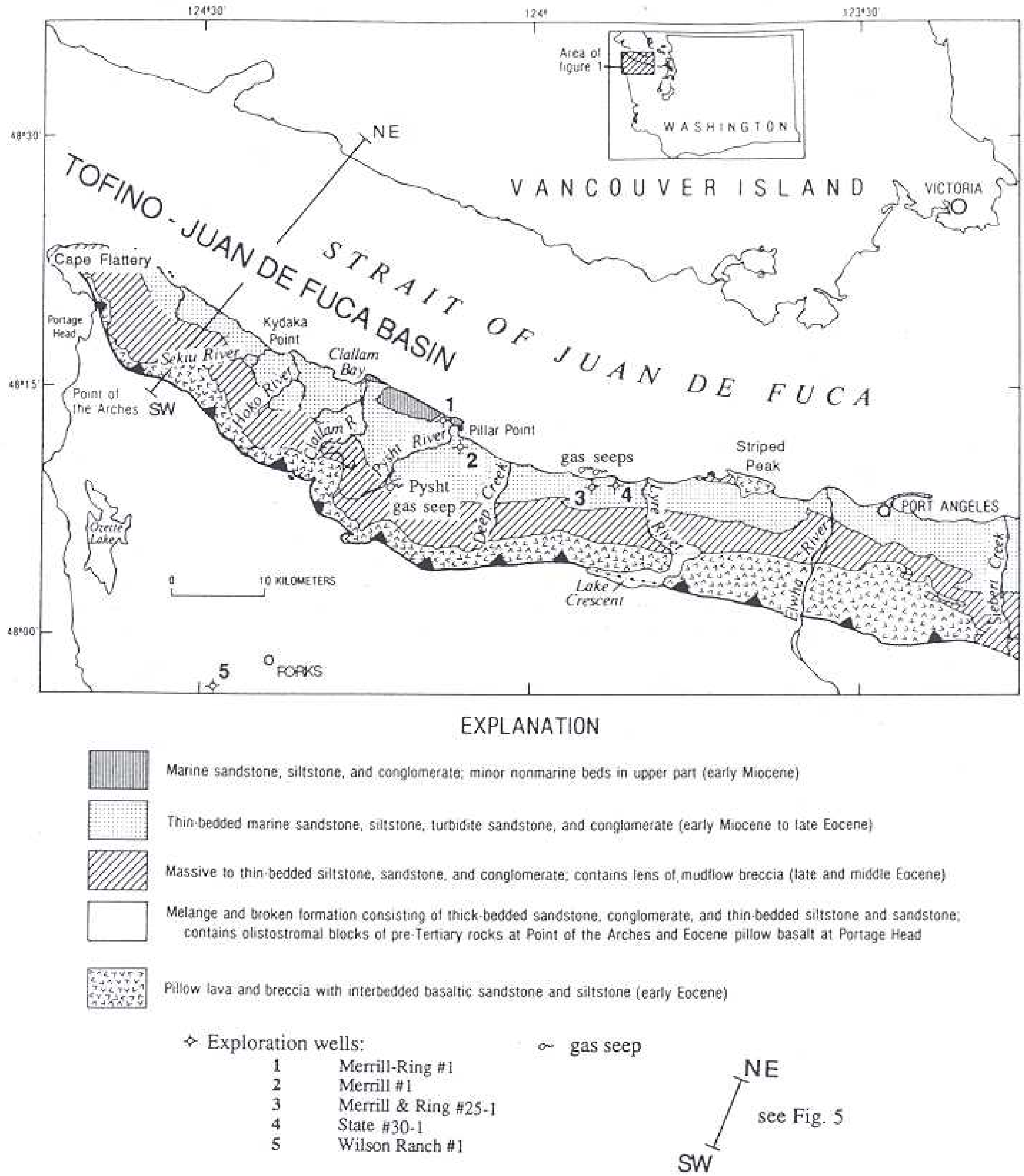

Figure 1. Location map of the Juan de Fuca area (redrawn from Snavely and others, 1980).

basalt of the Crescent Formation (Fig. 2). The sedimentary sequence is capped by a prograding, wave-dominated, deltaic facies of the coal-bearing lower Miocene Clallam Formation that filled this largely deep-marine basin (Gower, 1960; Anderson, 1985; Addicott, 1976). To the south, the Crescent basalt and marginal JDFB strata are underplated by several terranes of mélange and broken formation of the Olympic core rocks (Tabor and Cady, 1978), including the middle to upper Eocene Ozette terrane, the Jurassic to upper Eocene Sooes terrane, and the unnamed terrane between the

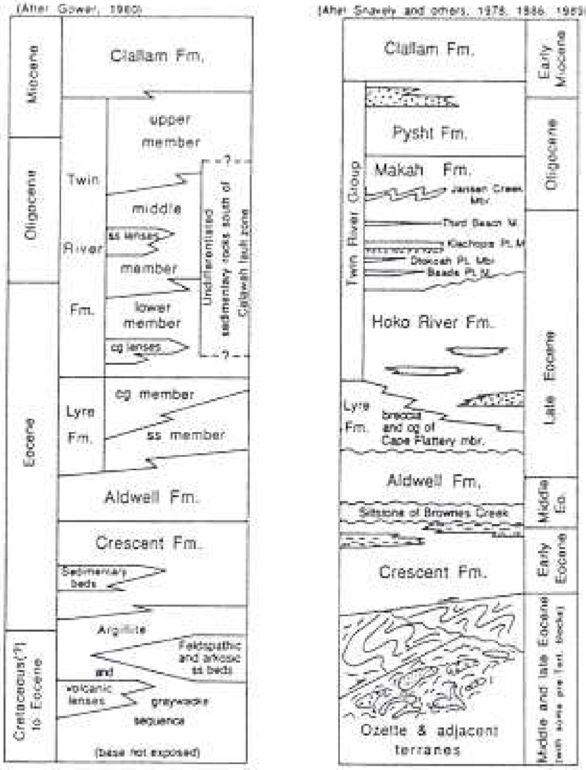

Figure 2. Stratigraphic columns for Juan de Fuca basin. The eastern part of the basin is represented by a column modified from Gower (1960); the western part of the basin is shown as interpreted by Snavely and others (1978, 1986, 1989).

Calawah fault and the Crescent thrust fault (Snavely and others, 1986; Snavely and Kvenvolden, 1989).

Depositional environments represented by the JDFB sedimentary rocks include (a) bathyal slope, outer fan, and basin-plain environments, indicated by thick mudstone deposits with minor thin distal turbidites and (or) locally derived debris flows (middle and upper Eocene Aldwell Formation – Snavely, 1983; Marcott, 1984; Oligocene and lower Miocene Pysht Formation – Snavely and others, 1978), (b) submarine fan cones or gravel slope wedges (upper Eocene Cape Flattery breccia and Lyre Formation – Brown and others, 1956; Ansfield, 1972; Alice Shilhanek, Western Wash. Univ., oral commun., 1991), (c) intraslope basin debris flows and middle to outer fan conglomerate channels (upper Eocene Hoko River Formation – Ansfield, 1987; De Chant, 1989), (d) depositional lobes in an outer- to mid-fan environment (upper Eocene and Oligocene Makah Formation – Snavely and others, 1980; and upper Eocene to lower Miocene Twin River Group – Brown and Gower, 1958, and Rau, 1964), and (e) submarine slumps (Jansen Creek Member of the Makah Formation – Snavely and others, 1980; Niem and others, 1989). Some Eocene shallow-marine basaltic sandstones fringe and are derived from and interbedded with flows associated with Crescent volcanic highs (for example, Striped Peak; Brown and others, 1960). The JDFB strata were largely derived from Mesozoic and Paleozoic low-grade metamorphic, granitic, volcanic, and recycled sedimentary source terranes on southern Vancouver Island (Snavely and others, 1980; Pearl, 1977; Ansfield, 1972; De Chant, 1989; Anderson, 1985) and from local Crescent/Metchosin volcanic paleohighs (Snavely, 1983; Brown and others, 1960; Marcott, 1984).

Few data have been published regarding the organic richness, maturation, porosity, and permeability of JDFB sedimentary units. (See Snavely, 1987; Snavely and Kvenvolden, 1989; Kvenvolden and others, 1989). Thus, these data may not be representative of the hydrocarbon potential of the entire basin. Total organic carbon (TOC) values for several outcrop samples of mudstone from these formations are typical of poor to fair source rocks (Table 1) (Peters, 1986). The oil and gas generative potential ($S_1 + S_2$) falls in the non-source rock category (Fig. 3A). These mudstones also display low hydrogen and oxygen indices (HI and OI, respectively, Table 1), and most samples plot on a van Krevelen diagram in a nondiagnostic area near the convergence of the Type III (gas-prone, terrestrial) and Type II (oil-prone, marine) kerogen curves (Fig. 3B). Low vitrinite reflectance (R_o), thermal alteration index (TAI), production index (PI), T_{max}, and transformational ratio (TR) values (Table 2) indicate that these samples are also thermally immature to marginally mature with respect to the peak oil generation window and immature with respect to the thermogenic wet and dry gas

Table 1. Source rock analyses of Tertiary siltstone, Juan de Fuca basin. TOC, total organic carbon; HI, hydrogen index = $(S_2/TOC)x100$; S_1+S_2 = oil or gas potential; OI, oxygen index = $(S_3/TOC)x100$

		Rock-Eval mg/g rock					
Formation	TOC	S_1	S_2	S_3	HI	OI	S_1+S_2
Pysht-1	0.87	0.02	0.47	0.21	54	24	0.49
Pysht-2	0.41	0.00	0.25	0.09	61	22	0.25
Pysht-3	0.45	0.04	0.37	0.01	82	2	0.41
Makah-4	0.34	0.01	0.18	0.07	52	20	0.19
Aldwell-5	0.44	0.04	0.28	0.06	64	14	0.32
Aldwell-6	0.34	0.00	0.20	0.13	59	38	0.20
Range	0.34	0.00	0.18	0.01	52	2	0.19
	0.87	0.04	0.47	0.21	82	38	0.49
Av. (n = 6)	0.48	0.02	0.29	0.10	62	20	0.31

Table 2. Maturation analyses of Tertiary siltstone, Juan de Fuca basin. R_o, vitrinite reflectance; PI, production index; TAI, thermal alteration index; TR, transformation ratio = $S_1/(S_1+S_2)$. (From Snavely and Kvenvolden, 1989)

			Rock-Eval		
Formation	R_o	TAI	PI	T_{max} (°C)	TR
Pysht-1	0.42	2.4	0.04	428	0.04
Pysht-2	0.48	2.5	0.00	430	0.00
Pysht-3	0.52	2.5	0.10	428	0.10
Makah-4	0.61	2.55	0.06	432	0.05
Aldwell-5	0.51	2.5	0.00	441	0.13
Aldwell-6	0.53	2.5	0.00	436	0.00
Range	0.42	2.4	0.00	428	0.00
	0.61	2.55	0.10	441	0.13
Av. (n=6)	0.51	2.5	0.03	433	0.05
Olympic core rocks Av. (n = 26)	0.75				

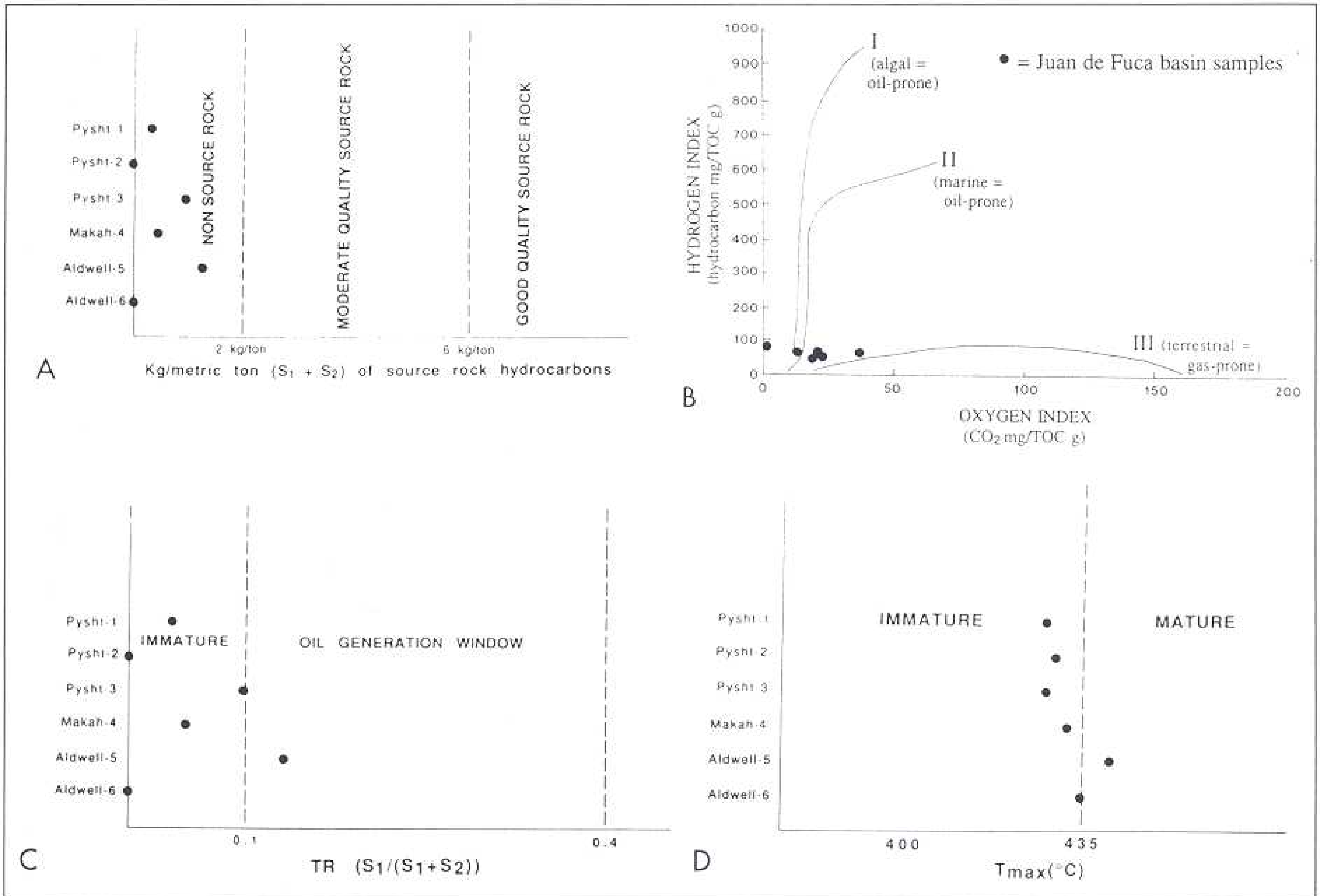

Figure 3. **A.** Classification of source rock quality of Juan de Fuca basin samples based on kilograms per metric ton (S_1 + S_2) of source rock hydrocarbons. (Bounding values from Tissot and Welte, 1978). **B.** Van Krevelen diagram (after Tissot and Welte, 1978) for Juan de Fuca basin samples reported in Snavely and Kvenvolden (1989). **C.** Source rock maturity evaluation diagram for Juan de Fuca basin samples based on transformation ratio (TR = $S_1/(S_1 + S_2)$) (oil generation window as defined by Tissot and Welte, 1978). **D.** Classification of source rock maturity for Juan de Fuca basin samples based on T_{max} (°C) (temperature ranges as shown by Espitalié and others, 1977). Sample values reported in Snavely and Kvenvolden (1989).

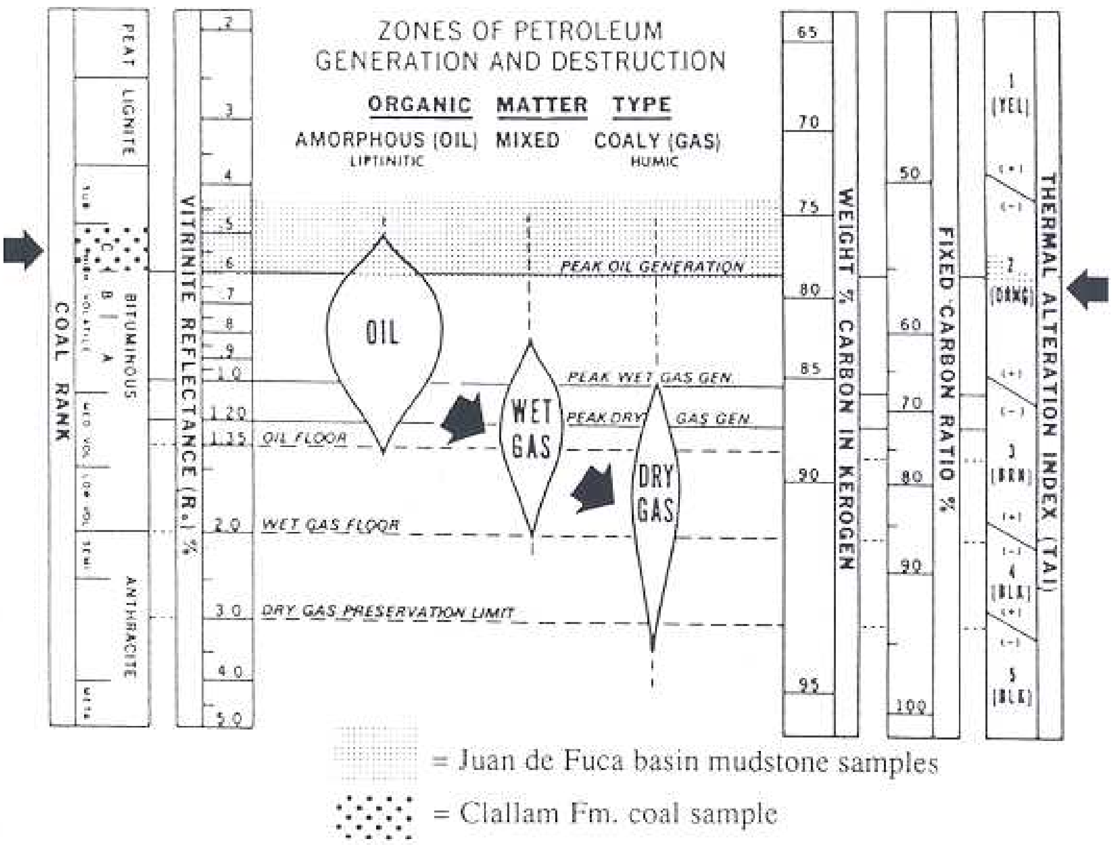

Figure 4. Correlation of various maturation indices (for example, R_o and TAI) with coal rank and zones of petroleum generation and destruction (modified from Dow, 1978). Juan de Fuca basin mudstone samples (reported by Snavely and Kvenvolden, 1989) plot in the stippled area on this diagram. Coal rank of the Clallam Formation was calculated by T. J. Walsh, Wash. Div. of Geol. and Earth Res., from an earlier published analysis by Smith (1911).

generation window (Figs. 3C, 3D, and 4) (Tissot and Welte, 1978; Dow, 1978). The HI, OI, S_1, S_2, S_3, PI, TR, T_{max} values, derived by Rock-Eval pyrolysis, however, can be affected by low TOC values, outcrop weathering, or adsorption of pyrolyzate on clay mineral matrix (Peters, 1986). The high volatile C bituminous rank of a Clallam Formation coal sample is consistent with the thermal immaturity of these mudstone samples (Fig. 4). In contrast, the more highly deformed middle and upper Eocene broken formation and mélange terranes of the northwest Olympic core rocks (that is, Ozette, Sooes, and unnamed terranes) exposed immediately south of the JDFB are generally thermally more mature (that is, an R_o average of 0.75 for 26 samples) (Table 2).

A natural seep in fractured Hoko River turbidite lithic sandstone and siltstone (lower Twin River Formation of Gower, 1960) along the Pysht River (Fig. 1) emits thermogenic gas (Snavely, 1987). The hydrocarbon and isotopic compositions of this gas are similar to those in thermogenic gas from the Wilson Ranch well in the Ozette mélange and broken formation to the south near Forks (Kvenvolden and others, 1989) (Table 3, and no. 5 on Fig. 1). This suggested to Snavely (1987) and Kvenvolden and others (1989) that the Pysht River gas may be sourced via deep-seated faults from the underlying Ozette mélange and broken formation and adjacent core rock terranes that have been underplated beneath the Crescent volcanic rocks and overlying JDFB fill (Fig. 5). The middle and upper Eocene Ozette mélange also includes oil-prone "smell muds" that contain thermogenic gas (Snavely and Kvenvolden, 1989). Thermogenic gas seeps in the JDFB have also been reported immediately offshore in the Strait of Juan de Fuca (Northwest Oil Report, 1986; Lingley, 1986) (Fig. 1).

Four exploration wells (as much as 8,519 ft total depth) have been drilled onshore in the eastern part of the JDFB (Nos. 1 through 4 on Fig. 1), mostly in the Eocene and Oligocene Twin River Group. Some oil and gas shows were reported (Northwest Oil Report, 1986, 1987; McFarland, 1983; unpub. drillers' logs from Dept. of Nat. Res. files). Hydrocarbon and isotopic analysis of a gas sample from the Twin River Oil and Gas State No. 30-1 well (drilled in 1986) showed that the gas is thermogenic (W. S. Lingley, Jr., Wash.

Table 3. Gas analyses for a natural seep and a test well, Juan de Fuca basin and Olympic core rocks (From Snavely and Kvenvolden, 1989)

Gas (volume %)	Pysht gas seep	Wilson Ranch well
Methane	94.33	95.8
Ethane	3.50	2.7
Propane	1.54	0.90
Butanes	0.43	0.30
Pentanes+	0.19	0.27
Methane Delta ^{13}C per mil	-31.5	-34.7
Hydrogen Delta D per mil	—	-135

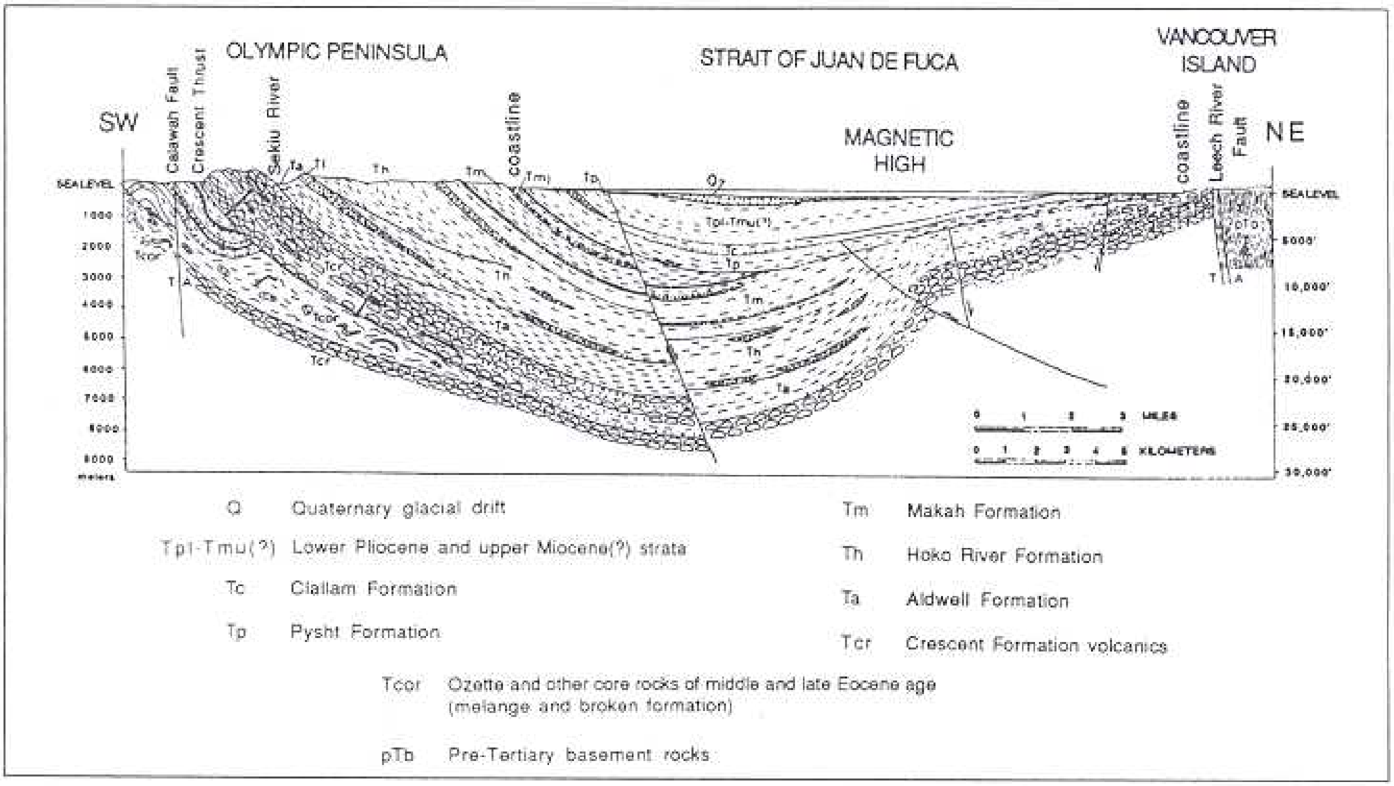

Figure 5. Generalized southwest-northeast cross section of the Juan de Fuca basin from the Olympic Peninsula beneath the Strait of Juan de Fuca to southern Vancouver Island (after Snavely, 1983). Location of cross section is shown on Figure 1.

Div. of Geol. and Earth Res. [DGER], oral commun., 1991). These shows may be sourced from underplated Ozette mélange and broken formation and adjacent core rocks or may have migrated updip from the more deeply buried, offshore part of the JDFB.

In general, the reservoir potential of the matrix-rich turbidite sandstone and conglomerate beds in the JDFB is low to moderate because abundant diagenetic and detrital clays, calcite, and minor zeolite and siliceous cements clog primary pores and pore throats (Pearl, 1977; Snavely and others, 1980; Ansfield, 1972; Anderson, 1985). Only a few values of porosity and permeability have been published for outcrop samples of members of the Makah Formation (Fig. 2; Snavely and others, 1980; Snavely, 1987). These values are lowest in the matrix-rich lithic and lithic arkosic wackes (for example, Baada Point Member, 20.4% and 20.7%, 2.0–7.5 md) but are moderately high in some cleaner micaceous arkosic sandstone units (for example, Klachopis Point Member, 24.6% and 657 md). These members represent thickening-upward, thick-bedded, sheet-like sandstones of mid- to outer-fan depositional lobes that can be traced laterally as much as 32 km in the western part of the JDFB (Snavely and others, 1980, 1986). Preliminary analysis of wireline logs from the Merrill–Ring No. 1 and Merrill No. 1 wells suggests that the penetrated section is dominantly siltstone, claystone, and minor thin, tight, distal turbidite sandstone (W. S. Lingley, Jr., DGER, oral commun., 1991). No significant reservoir sandstone was penetrated. Minor secondary fracture porosity in JDFB formations may have been created by faulting and jointing.

Potential seals occur in thick slope mudstone units and thin-bedded outer fan and basinal turbidite sandstone and siltstone facies (for example, Pysht, Makah, and Hoko River Formations of Snavely and others, 1978, 1980, and Twin River Formation of Gower, 1960). However, most of the homoclinal north-dipping potential reservoir units are breached by erosion. Possible stratigraphic traps include buried pinchouts of turbidite sandstone and conglomeratic inner-fan channel deposits in the Hoko River and Lyre Formations and depositional lobes of the Makah Formation that wedge out on Crescent paleohighs. (See Snavely and others, 1980.) Structural traps onshore are few and include local normal, strike-slip, and thrust faults as well as minor closure on faulted anticlines mapped by Snavely and others (1986, 1989), Gower (1960), and Brown and others (1960). These faults formed mainly in the late Eocene and late middle Miocene during periods of active underplating (Snavely, 1987). The timing of generation and migration of potential hydrocarbons relative to the timing of formation of potential structural and stratigraphic traps will require further investigation.

The Eocene and Oligocene turbidite units and lower Miocene deltaic Clallam Formation, which represent potential reservoirs, also extend offshore to the north and northwest. A thick lower Pliocene and upper Miocene(?) sedimentary sequence and Pleistocene glacial fill unconformably overlie these Paleogene and lower Neogene units beneath the Strait of Juan de Fuca and could act as possible seals (Fig. 5). Interpretation of U.S. Geological Survey seismic-reflection profiles (Snavely, 1987; Wagner and Tomson, 1987) and magnetic anomaly maps (MacLeod and others, 1977) (Fig. 5) suggests that structural traps (for example, thrusts and normal faults) may occur in this area. However, agreements between Canada and the United States currently preclude drilling in these environmentally sensitive waters. Exploration of these units on land may merit further study.

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Geothermal Projects at Mount Meager, British Columbia—History, Geology, Power Marketing, and Implications for the U.S. Cascades

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During the years 1973–1984, the British Columbia Hydro and Power Authority (B.C. Hydro), a Crown corporation, explored for geothermal resources at Mount Meager, 160 km (100 mi) north of Vancouver, B.C. (Fig. 1). The Geological Survey of Canada (GSC) and its parent, Energy, Mines and Resources Canada, also conducted seminal research, drilled several holes, and financially assisted B.C. Hydro.

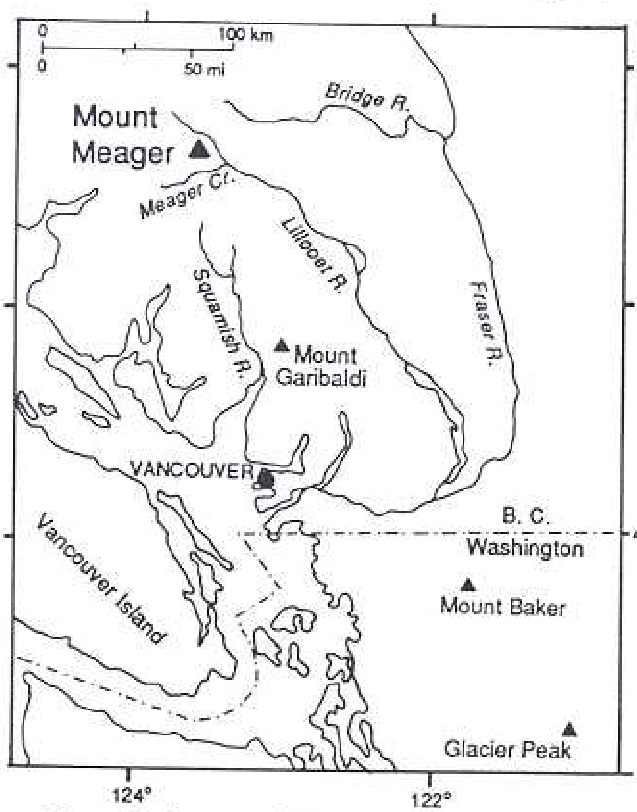

Figure 1. Location of Mount Meager, British Columbia.

The work discovered two high-temperature geothermal reservoirs, on the north and south flanks of Mount Meager. However, B.C. Hydro abandoned the project in the mid-1980s, during a period of diminished load growth, low energy prices, and high borrowing costs, and returned its geothermal tenure to the Province.

Interest in geothermal energy has picked up during the past few years, and private sector independent power producers (IPP) have resumed work where B.C. Hydro left off.

Geography and Physiography

Mount Meager is one of the northernmost volcanic complexes of the belt that extends from Mounts Lassen and Shasta in California through the Cascade chain of Oregon and Washington. In British Columbia, these volcanic rocks are called the Garibaldi belt.

The physiography of Mount Meager differs from that of Mount Baker, Mount St. Helens, and the other central volcanoes. Mount Meager was extruded on and among the rugged granitic peaks of the Coast Range. At Meager, the circular ramp of lava flows, lahars, and fanglomerates that surrounds most of the Cascade volcanoes has been dissected and removed by erosion, including glaciation. This has exposed the crystalline basement rocks on three sides. About 100 km^2 (40 mi^2) of volcanic rocks are exposed. Elevations in the area are from 400 to 2,800 m (1,300–8,790 ft).

Valleys are filled with alluvium, landslide debris, and till. Lower slopes are covered with first-growth fir, currently being logged. Treeline is at about 1,500 m (5,000 ft).